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ENERGY USAGE IN NATURAL GAS PIPELINE APPLICATIONS

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ABSTRACT

Energy required to transport the fluid is an important parameter to be analyzed and minimized in pipeline applications. However, the pipeline system requirements and equipment could impose different constraints for operating pipelines in the best manner possible. One of the critical parameters that is looked at closely, is the machines' efficiency to avoid unfavorable operating conditions and to save energy costs. However, a compression-transport system includes more than one machine and more than one station working together at different conditions. Therefore, a detailed analysis of the entire compression system should be conducted to obtain a real power usage optimization. This paper presents a case study that is focused on analyzing natural gas transport system flow maximization while optimizing the usage of the available compression power. Various operating scenarios and machine spare philosophies are considered to identify the most suitable conditions for an optimum operation of the entire system.

Modeling of pipeline networks has increased in the past decade due to the use of powerful computational tools that provide good quality representation of the real pipeline conditions. Therefore, a computational pipeline model was developed and used to simulate the gas transmission system. All the compressors' performance maps and their driver data such as heat rate curves for the fuel consumption, site data, and running speed correction curves for the power were loaded in the model for each machine. The pipeline system covers 218 miles of hilly terrain with two looped pipelines of 38″ and 36″ in diameter. The entire system includes three compressor stations along its path with different configurations and equipment. For the optimization, various factors such as good efficiency over a wide range of operating conditions, maximum flexibility of configuration, fuel consumption and high power available were analyzed. The flow rate was maximized by using instantaneous maximum compression capacity at each station while maintaining fixed boundary conditions. This paper presents typical parameters that affect the energy usage in natural gas pipeline applications and discusses a case study that covers an entire pipeline. A modeling approach and basic considerations are presented as well as the results obtained for the optimization.

NOMENCLATURE

Symbols

ΔP = System total pressure loses

1 COMPRESSION SYSTEM MODEL AND MAIN ASSUMPTIONS

An existing transmission compression system is required to increase its capacity while maintaining its normal gas transportation. Therefore, in order to meet the increasing capacity demand, an improved operation of the system is necessary while new investments on its transportation infrastructure are achieved. Thus, a model of the entire gas pipeline network was built using a commercial pipeline simulator package. The model covers the three main zones of the entire gas pipeline system: north, central, and south. The model includes primary components such as compressors, main pipelines and branches, regulators, valves, injection and extraction points, etc. In addition, delivery and injection points, compressor operating conditions, and average ambient temperature per zone were incorporated. The system includes approximately 218 miles of interconnecting pipelines, 3 main compressor stations, 3 different injection points, and 9 extraction locations. The total installed compression capacity for the entire system is approximately 416,000 hp including a 32% of required (base on contractual regulations) spare capacity. Each compression station has installed multiple centrifugal compressor machines operating in parallel with at least one machine on stand-by. The rated horse power for the machines varies from 13750 hp to 31250 hp.

The developed model takes into account heat transfer with the surroundings, changes in elevation, flow and pressure regulation points as well as diverse operating conditions. Simulation scenarios cover a wide variety of flow and pressure conditions. Parameters such as roughness, heat transfer coefficients, and ground thermal conductivity are set as average values for the type of soil and ambient conditions [1, 2, 3]. No tuning of the model was possible due to the lack of real operating data. A general schematic of the pipeline system is presented in Figure 1-1.

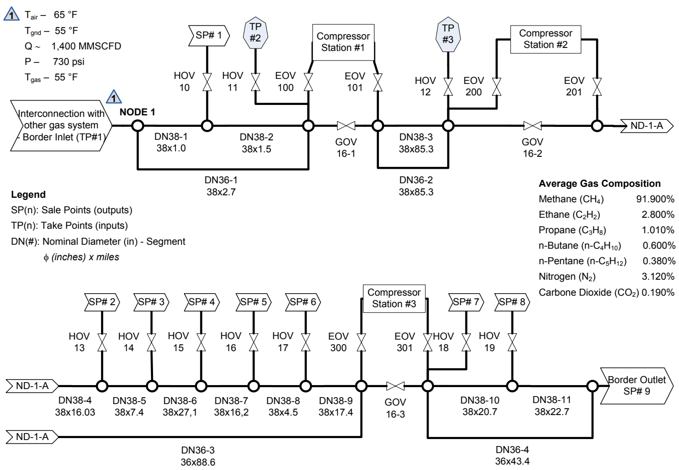

Figure 1-1. General Schematic of the Pipeline System

Gas composition was specified at each injection point based on the data provided. Different gas compositions were incorporated into the model in order to represent the real properties of the gas stream in the pipeline. Mixing of the different gas streams was performed in the pipeline based on the respective pressure, temperature, and compositional makeup of each stream and on the assumption of fully turbulent mixing of the gas.

Initial line packing was not assumed since the real system operates at constant flow rates and pressures due to operational constraints of MAOP and contractual requirements. Therefore, a mass balance was assumed (steady-state conditions; mass in = mass out). This mass balance was accomplished through pressure injection points. Flow extraction points were maintained as initial input. Thus, this mass balance assumption was fully applicable for each simulation case.

Ground temperature profiles and heat transfer coefficients were defined, so the simulation was run assuming heat transfer between the gas stream, the piping, and the surrounding ground. An average temperature for the ground was considered for each sub-zone of the model, based on the average ambient temperature and considering a margin of +2ºF. At pipeline depths of about six meters or more, there is no significant change from summer to winter, and the mean ground temperature approaches the annual average air temperature plus 2°F. The ground temperature changes very slowly, generally not more than two or three degrees Fahrenheit unless there has been a cold rain in the fall or a warm rain in the spring. Factors that determine the temperature of the ground can be grouped in three general categories: meteorological, terrain, and subsurface variables. Large-scale regional differences in ground temperature are determined primarily by meteorological variables such as solar radiation, air temperature, and precipitation. Micro or local variations are caused by differences in terrain, surface characteristics, and ground thermal properties. The properties of the ground that determine its response to temperature changes at the surface are volumetric heat capacity, C, thermal conductivity, K, latent heat (the heat required to freeze or thaw a unit volume of frozen soil), and water content. The ratio, K/Cv, known as thermal diffusivity, is important in calculating rate of heat flow in the ground [3].

In conclusion, for depths below five to six meters, ground temperatures are essentially constant throughout the year. The average annual ground temperature is practically constant with depth, increasing about 2ºF per 50 meters due to geothermal heat flow from the center of the earth to the surface.

2 COMPUTATIONAL MODEL MAIN ASSUMPTIONS

Computational modeling requires a clear understanding of the real process or phenomenon to be simulated, since many real conditions are approximated or averaged to simplify the modeling process. However, an adequate model must incorporate physical parameters to avoid significant differences in the modeling results. Therefore, some of the most important variables, parameters, and criteria used in this study were assessed and reviewed. In the following points, a brief review of the most important parameter and assumptions is presented.

Temperature Conditions

Temperature affects many parameters in gas transmission systems such as pipeline transport capacity, compression energy, formation of hydrates, hydrocarbon condensation, and pipeline material thermal stresses. Conductive and convective heat transfers affect the gas temperature in the pipeline. In addition, the surrounding soil and the Joule-Thomson effect will influence the gas temperature. Therefore, it is critical to apply the correct temperature value when simulating a gas pipeline system [4, 5, 6].

When calculating the transport capacity and compression energy, the temperature value will change based on the location and season of the year. There is not a specific value assumed for the wide variety of applications and locations. In general, machines' specifications are always related back to ISO conditions. However, the minimum equipment requirements are calculated for the actual process requirements and site conditions and then extrapolated to ISO conditions for a more accurate selection. For example, a gas turbine design power is corrected by elevation and ambient temperature to obtain the real output value at the desired conditions. Correction factors are provided by the Original Equipment Manufacturer (OEM), and they should be utilized for the proper power and heat rate calculations.

Gas transporting companies calculate their capacity based on the season, since it will increase during the winter and decrease during the summer due to the temperature effect. During the summer the high temperatures reduce the performance of the prime movers, Gas Turbines (GT); the increased gas temperature in the pipeline requires more energy to compress the gas and increases the frictional pressure losses. The lower temperatures during the winter aid the gas transport system with an inverse effect [7].

Internal Pipe Roughness

Generally, in high pressure gas transmission pipelines, the high flow rates lead to fully turbulent flow. Thus, the effective roughness of the pipeline is approximately equal to the internal surface roughness of the pipe, since the effect of the laminar sub-layer friction is negligible. The surface roughness plays an important role in accurately calculating the flow and energy loss due to friction in the pipe.

In general, the effective roughness values that are normally measured and used for uncoated commercial pipes are within the range of 17-19 μm. In addition, those values may increase due to erosion, corrosion, or contamination. This increase has been found to be approximately between 0.7-1.2 μm over a one-year period. Thus, it will affect the power requirements and flow capacity of the pipeline system if no regular maintenance is in place.

Internal coatings are used to reduce the effective roughness and provide protection against corrosion. However, the application of internal coating is essentially a life-cycle cost / benefit decision considering the entire technical and economical impact. Pipelines coated with materials like epoxy or polyamide have shown a reduction in effective roughness within a range of 5-7 μm. In general terms, the percentual impact of the effective roughness on the pipeline flow capacity will be between 1.25-1.5% [8] when the roughness differences are in the range of 25 μm.

Fuel Gas Consumption at the Compressor Stations

Fuel consumption depends on the type of machine, power, speed, and load, and site conditions. The amount of fuel consumed by a gas turbine is calculated by dividing its heat consumption by the fuel heating value. Thus, the heat consumption is computed by multiplying the corrected gas turbine heat rate by the corrected power. Therefore, the amount of fuel consumed by the machine depends directly on its heat rate.

Station Configuration and Spare Criteria

In gas transmission systems, the design philosophy for choosing a compressor should include the following considerations:

- ☐ Good efficiency over a wide range of operating conditions
- ☐ Maximum flexibility of configuration
- ☐ Low maintenance cost
- ☐ Low lifecycle cost
- ☐ Acceptable capital cost
- ☐ High availability

However, additional requirements and features will depend on each project and the specific experiences of the pipeline operator. In fact, compressor selection and layout is defined by the operating parameters for which the machine will be intended. Design parameters specific to the selection such as flow rate, gas composition, inlet pressure and temperature, outlet pressure, train arrangement, compressor series or parallel configurations, multiple bodies, multiple sections, intercooling, etc., will delimit the performance characteristics of the compressor station.

Usually a hydraulic analysis is performed for each compressor selection to ensure the best choice. In fact, compressor selection can be made for an operating point that will be the most likely or most frequent operating point of the machine. Selections based on a single operating point have to be evaluated carefully to provide sufficient speed margin (typically 5-10%) and surge margin to cover other potentially important situations. A compressor performance map (for centrifugal compressors, this would preferably be a head versus flow chart at different speeds) can be generated based on the selection and is used to evaluate the compressor for other operating conditions by determining the required head and flow.

In many applications, multiple operating points are available, for example, based on hydraulic pipeline studies or reservoir studies. Some of these points may be frequent operating points while some may only occur during upset conditions. With this knowledge, the selection can be optimized for a desired target, such as lowest fuel consumption. Selections can also be made based on a “rated” point, which defines the most onerous operating conditions (highest volumetric flow rate, lowest molecular weight, highest head or pressure ratio, and highest inlet temperature). In this situation, however, the result may be an oversized machine that does not perform well at the usual operating conditions [9].

Another limiting factor in the determining the transport capacity of a pipeline system is the Maximum Allowable Operating Pressure (MAOP) of the pipe. When the available-installed compression capacity exceeds the limits of the pipeline MAOP, the system capacity is restricted by its physical limitations of the system. Therefore, a balance between the power installed and MAOP value provide the proper conditions for setting the design capacity of a pipeline system.

Standby Units or Sparing Philosophy

Selection of the appropriate number of machines for application in pipeline systems is based on diverse parameters such as flow and pressure, unit's availability and reliability, economic strategies, and commercialization (market offer supply and demand). There is no unique answer for all cases. Other factors such as driven power and its temperature effect may be considered in the final decision. When planning the operation of a compressor station, there are certain considerations for keeping one or more standby units. The first consideration involves the ability to manage the flow capacity changes over a period of time (i.e., hourly, daily, and seasonally) as well as changes in available power. Steady state and transient capabilities must be included in the system requirements as well as future growth and potential system upgrades.

Failure or unavailability of compressor units can cause significant losses in capacity, so the installation of standby units must be considered. These standby units can be arranged such that each compressor station has one standby unit, or that some stations have a standby unit, or that the standby function is covered by oversizing the drivers for all stations. It must be noted that the failure of a compression unit does not mean that the entire pipeline ceases to operate, but rather that the flow capacity of the pipeline is reduced. Since pipelines have a significant inherent storage capability (line pack), a failure of one or more units does not have an immediate impact on the total throughput. Additionally, planned shutdowns due to maintenance can be scheduled during times when lower capacities are required [10].

Availability plays a significant role in determining the requirement for spare units in a station or along the pipeline. If units become unavailable, either due to planned maintenance or due to unplanned failures, the pipeline capacity is reduced. Since many pipeline operations have to guarantee a certain minimum flow, this minimum flow becomes a planning criteria for the spare unit requirements, based on the reliability and availability of individual units and components. Total cost of ownership and life cycle cost are influenced by first cost, but also by the efficiency of operation. Contractual obligations play an important role since most of the contractual capacity is on a firm basis and subject to liabilities related to capacity shortage or interruption. Compressor station availability studies play a fundamental role in providing information that will support decision making in terms of defining a criterion for installing stand-by units. Therefore, each transporting gas company evaluates its technical limitations and balances them with its contractual obligations to define the proper spare criteria to be applied.

Some of the methods adopted by transporting gas companies include analysis such as Monte Carlo Simulations, scheduled and unscheduled maintenance, and binomial distribution for calculating unit availability or unavailability. Economical considerations are always part of the process to identify the adequate quantity of standby units to provide a manageable level of risk exposure to contractual liabilities due to non-delivered capacities. The Monte Carlo simulation method associated with scheduled and non-scheduled maintenance provides quick and reliable results to be used by the decision makers in defining the necessary level of redundancy for the gas pipeline transmission system [11].

The availability and reliability values of a unit play an important role in determining the amount of spare capacity. Evaluation of the availability and its effect is recommended during the design phase of the gas pipeline project in order to define the appropriate load factor to be adopted for the project, or to negotiate appropriate level of commitment of contractual firm capacity. For this particular case study the spare units requirements were stated by the pipeline operator based on internal regulations of the company since they have a ship or pay contract. So, they are required to have enough available and spare capacity to avoid penalties.

3 FLOW MAXIMIZATION AND POWER USAGE METHODOLOGY

In recent years, pipeline optimizer packages have become very popular and useful for gas transporting companies. Many of those softwares look for more than one optimum condition for the entire system since locals and global optimum values can be calculated. However, many constraints have to be verified before declaring an optimal condition. Usually, different linear and non linear solvers are used to find and determine an optimum operating condition for the entire system. In general terms, an optimization means transporting more using minimum amount of required power while improving the system efficiency. Different strategies are used to obtain an optimum condition such as line packing and unpacking, higher compression efficiency (machines and gas cooling), less friction loses, and compression power usage [12, 13, 14, 15]. The case presented in this paper has been focus on improving the operation of the system by optimizing the use of the installed power while maximizing the total transported flow rate. It is important to understand that the overall efficiency of the transportation network is controlled by the correct application of compression along the system and flow and pressure regulation. Therefore, a simplified method for optimizing the performance of the overall system was applied in this case. This method focuses on three basic parameters: total throughput of the system, total fuel used in the compression, and compression power usage and efficiency. In addition, this optimization considers the different explicit and implicit system constraints such as MAOP, maximum power available, stand-by philosophy, required input/output flows, different season's ambient conditions, minimum and maximum compressor flow, surge and stonewall margin, as well as compression ratio limitations.

The optimization modeling approach utilized in this case study was very specific to the pipeline transport system in consideration. However, it can be adapted to other systems with similar characteristics. This approach considers all the compressors' maps and their driver data as they were loaded in the pipeline model. The software calculates the operating points of each compressor unit based on flow and pressure ratio conditions (possible maximum) as well as the power available after considering all the driver corrections factors (i.e., power versus inlet ambient temperature, and elevation and GT speed curves). Those factors are loaded into the compressor model combining all the derating factors in one value that limit the maximum available power based on the instantaneous operating conditions of the machine. The flow rate is distributed within the machines considering the best operating point for a given pressure ratio; so, higher efficiencies are achieved for each machine. The inlet and outlet system pressures are used as boundary conditions while the total flow is determined by the running-available compression capacity. The flow rate is calculated by using the available compression capacity at each station. This is accomplished by dividing the total station flow by the total power fraction of each compressor considering the best efficiency condition of each unit for the required pressure ratio. In addition, maximum pressure set points are established in each compressor station considering the MAOP of the pipeline system. After the flow is calculated based on the pressure boundary conditions and running units, the power usage, and surge and stone wall margins of each machine are evaluated to ensure they are acceptable.

Compressor operating parameters are calculated by the software in each iteration, and they are reported in the last iteration. After each iteration the ratio between the total flow and the total fuel gas flow is calculated; thus, an effective total flow ratio is obtained. In addition the, power usage is defined as the ratio between the used compression power and the available installed power, this parameter is monitored to obtain an optimum-maximum value for a given operating condition. Three main parameters were defined as guidelines to obtain an optimized scenario, and they are presented below in equations 1 through 3. For a single case the different iterations of those parameters were monitored until an optimal condition was reached. In addition, different cases were simulated considering various unit configurations for each station as well as pressure ratios. A schematic of the optimization modeling methodology used is presented in Figure 3-1.

$$\textit{Equivalent Transport Energy} = \frac{\textit{Used Compression Power} + \textit{Cooling Power}}{\Delta P * \textit{Total Transported Flow}} \quad (1)$$

$$\textit{Power Usage} = \frac{\textit{Used Compression Power}}{\textit{Available Installed Power}} \quad (2)$$

$$\textit{Effective Total Flow Ratio} = \frac{\textit{Total Transported Flow Rate}}{\textit{Total Fuel Consumption}} \quad (3)$$

A cascade method was applied for the optimization of the entire system starting with a local optimum for each compressor station and ending with a global condition for the entire pipeline system. Since the compressor stations have similar unit configurations, it was simpler to balance the compressor power along the system while maintaining optimum distribution of the used power and low equivalent transport energy. Moreover, similar compression distribution rates were used for each station since they exhibit an equal configuration and consider the same stand-by philosophy; however, some of them did not present similar derating.

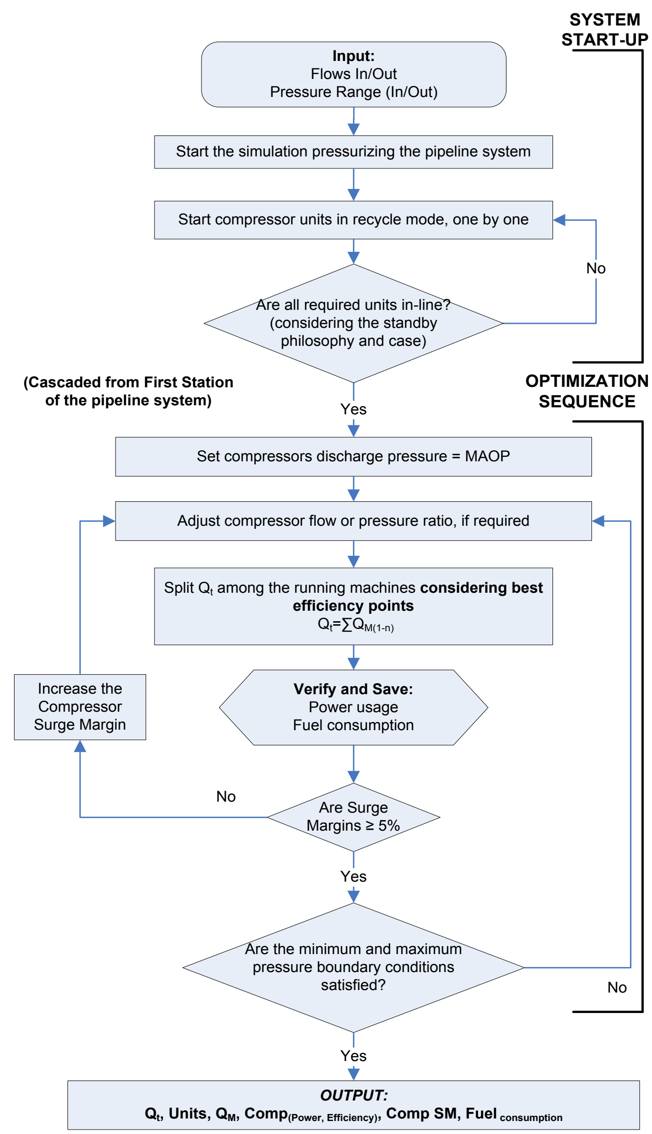

Figure 3-1. Optimization General Methodology Algorithm

4 COMPUTATIONAL MODEL RESULTS AND ANALYSIS

The pipeline system was modeled over a range of operating conditions and cases. The cases were defined based on their unit configuration and pressure set points. Thus, various optimized conditions were obtained for the operation of the system. A brief description of the simulated cases is presented in Table 4-1. The results obtained from the pipeline simulation include pressure, temperature, flow, and elevation profiles as shown in Figure 4-1. Other important parameters monitored during and after each simulation were pressure ratios, compression power and efficiency, flow rates, power usage, fuel consumption, and transport energy. Results of the most relevant cases are summarized in Table 4-2. This summary table presents the optimized scenarios obtained from different simulation cases as well as their optimization parameters results. The analysis of the results focuses only on the hydraulic of the pipeline system since economical and reliability considerations were not part of this study. Therefore, more than one feasible technical solution was obtained in this analysis. Moreover, the results of this hydraulic analysis can be combined with business analysis to obtain a techno-economical optimization of the system.

Table 4-1. Simulated Cases System Configuration Summary

CASE	Total Number of Centrifugal Compressor Units Operating in the Entire System	Total used Compression Power (hp)	Total Transported Flow Rate (MMSCFD)
Case 1	15	225963	3865
Case 2	16	249156	4153
Case 3	18	293805	4304
Case 4	14	205637	2954
Case 5	14	199508	3020

The example results presented in Figure 4-1.A. and Figure 4-1.B. represent a typical case for a gas transport system where the increase in pressure and temperature can be observed at each compressor station while the pressure energy losses and the heat transfer occur along the pipeline system. It is clear that considerable changes in the elevation would affect the energy loss due to the change in potential energy as presented in this system. In addition, injection and extraction points could affect the pressure and temperature in the pipeline. However, their effect will be directly depending on the amount of mass extracted or injected in the system. For example, at approximately mile 195 is an extraction point or customer that takes a considerable volume from the system, and it can be identified clearly as the pressure drop significantly in that specific point in the system. Other useful pieces of information that can also be obtained from the profiles are critical changes in diameters or geometry, loops or system interconnections, localized pressure drops, and changes in the terrain or soil conditions.

The system pro-rated average compression efficiency was defined as the *horse power* – efficiency ratio value of all the compressors that were running at one particular condition. This value is a good indication for optimizing the system compression since a flow split through a machine can affect its efficiency when the pressure ratio is maintained constant. One of the objectives of an optimization is to reduce the energy losses in transportation of the fluid, and it is accomplish by determining the adequate combination of energy use versus the total amount of fluid transport. In some cases the energy optimization leads to a lower flow rate than the maximum that could be reached for a particular system. Therefore, it is important to determine which the most relevant parameter in the optimization process is to obtain more adequate results. In order to quantify the optimization results, a change (increase/decrease) in the total transported flow rate was calculated for each case using as a reference the actual operating flow condition of the pipeline system.

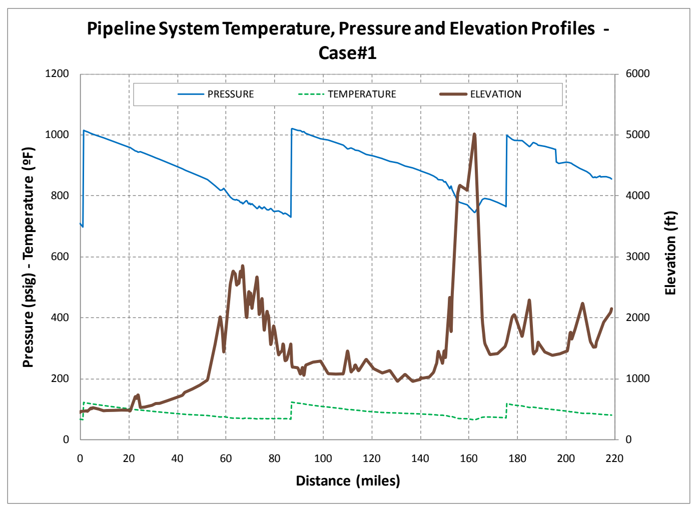

Figure 4-1.A. Pressure, Temperature and Elevation Profiles Example Results

Figure 4-2 shows the results of the five cases summarized for this case study. Case 3 represents the best optimum condition found for the operation of the system, the power usage and compression efficiency were maximized and the total flow transported increased by approximately 12.6%. This case involves a change in the operating philosophy of the units (higher discharge pressure set points) as well as a reduction of 20% of the spare capacity, leaving at least one unit as spare for station. Thus, contractual requirements were satisfied. The maximum system compression efficiency obtained in this case was a combination of efficiency optimization and rearrangement of machines operation. Although a maximization of the flow was achieved for this scenario, the equivalent transport energy represents the worst case condition due to higher friction losses originated by the increase in the flow rate and some additional cooling power added after the compression. The increase in transport energy was in the order of 2.9%.

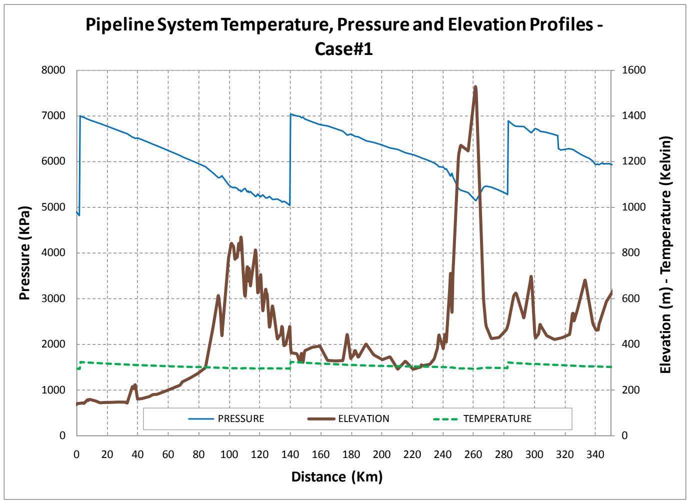

Figure 4-1.B. Pressure, Temperature and Elevation Profiles Example Results (SI Units)

Case 2 presented the lowest transport energy for the pipeline system with an increase of approximately 8.6% in the total transported flow rate. Thus, this is a second optimized scenario for the operation of the system. Moreover, the spare capacity was maintained at 25% and the effective total flow ratio was the second highest value obtained for the system in combination with the compression efficiency. Therefore, from the hydraulic stand point of view this case represents a good optimum condition as well. Case 1 was an optimization of the existing operating philosophy; so, the flow distribution through the compressors was optimized considering the highest efficiency values of the compressors. Thus, this case result indicates that minor changes in the current operation of the system could lead to a higher flow condition while maintaining the same unit configuration and spare capacity. An increase in the compression efficiency and a minor decrease in the transport energy resulted in an increase of 1.12% in the total transported flow rate.

New unit configurations and a more conservative spare philosophy resulted in a decrease of the total transported flow rate as shown in Figure 4-2 and Figure 4-3 for Cases 4 and 5. In both scenarios the power usage dropped near to 60% while the compression efficiency stayed in acceptable values around 78%. The maximum compression efficiency obtained in all the simulated cases was near 80%. In general, all cases presented good compression efficiency above 78%; this is due to the optimization process carried out with the simulator where each station was operated at the maximum possible efficiency value for a specific compression ratio allowing changes in the flow and speed of each machine. The reduction in the flow rate observed for Cases 4 and 5 was 2.1% and 2.27%, respectively, indicating that those scenarios do not represent good conditions for the operation of the system. In general, it was found that the system optimization was very sensitive to the compression capacity and efficiency since minor changes in the spare philosophy and units operation resulted in significant variations in the total transport flow rate and general system efficiency.

Table 4-2. Optimization Results Summary

CASE	System Pro-Rated Average Compression Efficiency (%)	Effective Total Flow Ratio (ETFR) (%)	Equivalent Transport Energy (hp/psi*MMSCFD)	Power USAGE (%)	Change in the Total Transported Flow (%)
Case 1	78.61	90.6	0.06200	68.4	1.12
Case 2	79.42	89.0	**0.06159**	75.1	8.66
Case 3	**79.48**	79.4	0.06341	**87.7**	**12.60**
Case 4	78.16	76.9	0.06292	62.0	-2.10
Case 5	78.39	80.8	0.06197	60.5	-2.27

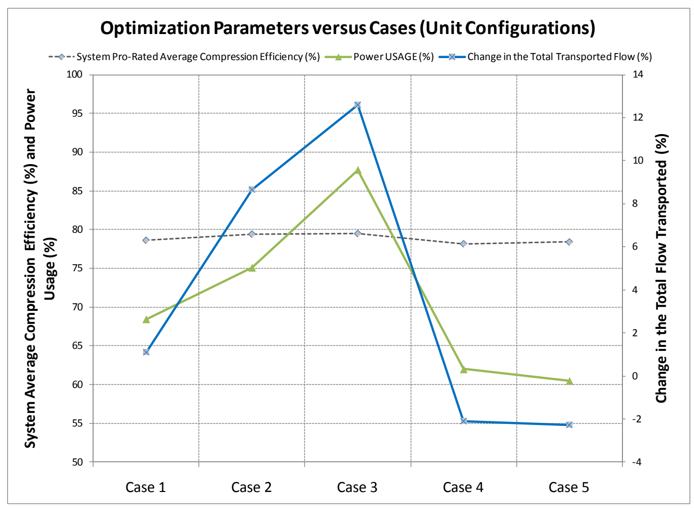

Figure 4-2. Compression Efficiency, Power Usage and Change in the Total Flow Transported for the Most Representative Cases

A further comparison of the equivalent transport energy is presented in Figure 4-4. For this comparison Case 2 was set as a reference for being the lowest value obtained for all the cases simulated. This comparison indicates a variation of 0.7-2.9% in the transport energy for the cases that presented an increase in the amount of flow transported.

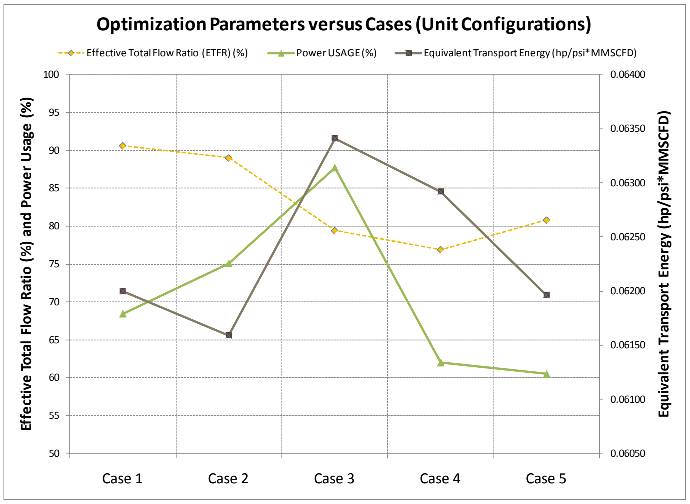

Figure 4-3. Effective Total Flow Ratio, Power Usage and Transport Energy Results

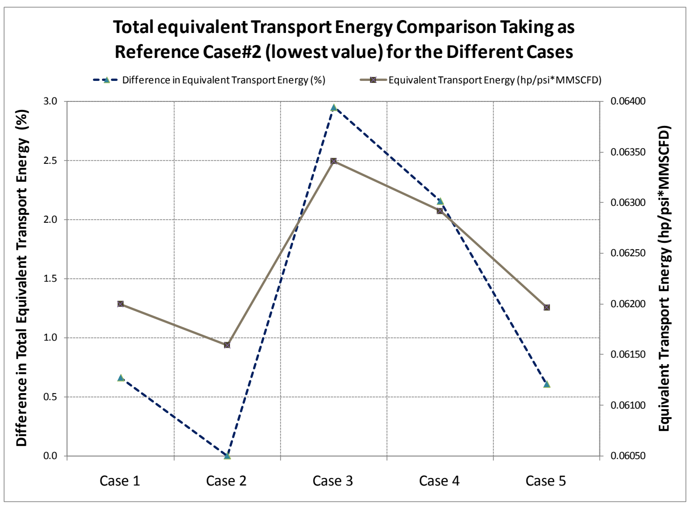

Figure 4-4. Comparison of Total Equivalent Transport Energy Results

5 ECONOMIC ANALYSIS

A basic economic analysis of the optimization results indicated additional revenue of 11.2% when the Case 3 configuration is used. This economical analysis includes the fuel and gas delivery costs only. Thus, the machine maintenance, degradation, additional investment, and other operational costs were not considered in this analysis. Moreover, the optimization results were included by a third party in an economical model that considers the Return of Investment (ROI), amortization rates, minimum profit margins, and risk to obtain a more detail economical evaluation of the optimized cases. Figure 5-1 presents the results of the basic economical analysis.

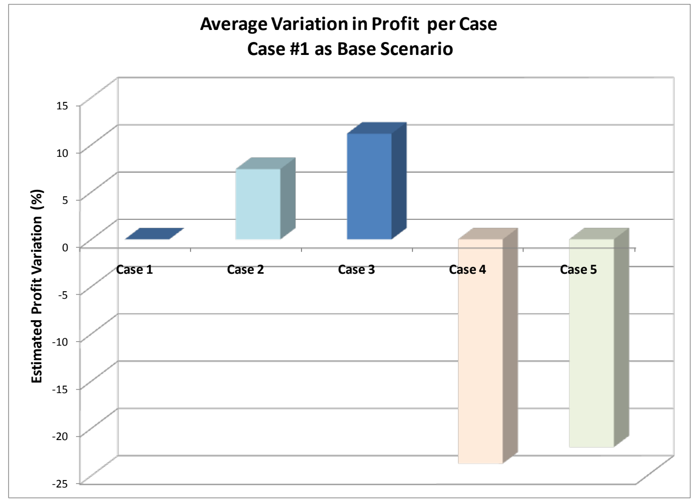

Figure 5-1. Estimated Profit Variation per Case

6 SUMMARY

The optimization methodology applied in this case study has provided two optimum cases for the improvement of the system operation. Those two cases resulted in a 8.6% and 12.6% increase in flow for the entire system. Therefore, these results have been considered satisfactory and relevant for defining new operating philosophies for the gas transporting system analyzed. Thus, the general objective of the optimization was accomplished, since various optimized operating scenarios were found while maintaining the required constraints for the system. These optimized scenarios have presented an efficient and optimum movement of natural gas through an extensive and elaborate transportation system. Moreover, these results will be used in conjunction with an economical study that would lead to a final conclusion about the new operating philosophies for this particular system while trying to satisfy the new market demands.

The parameter results to be used from this study are compressors' pressure set points and flow split, unit configurations, and spare philosophy. Thus, these parameters can be easily modified in the centralized gas control and compressor stations while flow rate, operational status, pressure, and temperature data along the entire pipeline may all be used to assess the status of the pipeline at any time through a centralized Supervisory Control and Data Acquisition (SCADA) system. Moreover, other operational constraints would be monitored and controlled from the SCADA providing the ability to remotely operate certain equipment along the pipeline, including compressor stations, allowing the operators to immediately and easily adjust any condition in the pipeline while keeping an optimum and safe transport of the gas.

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